ICE AGE IMPACT

A large asteroid struck Greenland in the time of humans. How did it affect the planet?

By **Paul Voosen**

On a bright July day 2 years ago, Kurt Kjær was in a helicopter flying over northwest Greenland—an expanse of ice, sheer white and sparkling. Soon, his target came into view: Hiawatha Glacier, a slow-moving sheet of ice more than a kilometer thick. It advances on the Arctic Ocean not in a straight wall, but in a conspicuous semicircle, as though spilling out of a basin. Kjær, a geologist at the Natural History Museum of Denmark in Copenhagen, suspected the glacier was hiding an explosive secret. The helicopter landed near the surging river that drains the glacier, sweeping out rocks from beneath it. Kjær had 18 hours to find the mineral crystals that would confirm his suspicions.

What he brought home clinched the case for a grand discovery. Hidden beneath Hiawatha is a 31-kilometer-wide impact crater, big enough to swallow Washington, D.C., Kjær and 21 co-authors report this week in a paper in *Science Advances*. The crater was left when an iron asteroid 1.5 kilometers across slammed into Earth, possibly within the past 100,000 years.

Though not as cataclysmic as the dinosaur-killing Chicxulub impact, which carved out a 200-kilometer-wide crater in Mexico about 66 million years ago, the Hiawatha impactor, too, may have left an imprint on the planet's history. The timing is still up for debate, but some researchers on the discovery team believe the asteroid struck at a crucial moment: roughly 13,000 years ago, just as the world was thawing from the last ice age. That would mean it crashed into Earth when mammoths and other megafauna were in decline and people were spreading across North America.

The impact would have been a spectacle for anyone within 500 kilometers. A white fireball four times larger and three times brighter than the sun would have streaked across the sky. If the object struck an ice sheet, it would have tunneled through to the bedrock, vaporizing water and stone alike in a flash. The resulting explosion packed the energy of 700 1-megaton nuclear bombs, and even an observer hundreds of kilometers away would have experienced a buffeting shock wave, a monstrous thunderclap, and hurricane-force winds. Later, rock debris might have rained down on North America and Europe, and the released steam, a greenhouse gas, could have locally warmed Greenland, melting even more ice.

The news of the impact discovery has reawakened an old debate among scientists who study ancient climate. A massive impact on the ice sheet would have sent meltwater pouring into the Atlantic Ocean—potentially disrupting the conveyor belt of ocean currents and causing temperatures to plunge, especially in the Northern Hemisphere. "What would it mean for species or life at the time? It's a huge open

IMAGE: NASA SCIENTIFIC VISUALIZATION STUDIO

A 1.5-kilometer asteroid, intact or in pieces, may have smashed into an ice sheet just 13,000 years ago.

question," says Jennifer Marlon, a paleoclimatologist at Yale University.

A decade ago, a small group of scientists proposed a similar scenario. They were trying to explain a cooling event, more than 1000 years long, called the Younger Dryas, which began 12,800 years ago, as the last ice age was ending. Their controversial solution was to invoke an extraterrestrial agent: the impact of one or more comets. The researchers proposed that besides changing the plumbing of the North Atlantic, the impact also ignited wildfires across two continents that led to the extinction of large mammals and the disappearance of the mammoth-hunting Clovis people of North America. The research group marshaled suggestive but inconclusive evidence, and few other scientists were convinced. But the idea caught the public's imagination despite an obvious limitation: No one could find an impact crater.

Proponents of a Younger Dryas impact now feel vindicated. "I'd unequivocally predict that this crater is the same age as the Younger Dryas," says James Kennett, a marine geologist at the University of California, Santa Barbara, one of the idea's original boosters.

But Jay Melosh, an impact crater expert at Purdue University in West Lafayette, Indiana, doubts the strike was so recent. Statistically, impacts the size of Hiawatha occur only every few million years, he says, and so the chance of one just 13,000 years ago is small. No matter who is right, the discovery will give ammunition to Younger Dryas impact theorists—and will turn the Hiawatha impactor into another type of projectile. "This is a hot potato," Melosh tells *Science*. "You're aware you're going to set off a firestorm?"

IT STARTED WITH a hole. In 2015, Kjær and a colleague were studying a new map of the hidden contours under Greenland's ice. Based on variations in the ice's depth and surface flow patterns, the map offered a coarse suggestion of the bedrock topography—including the hint of a hole under Hiawatha.

Kjær recalled a massive iron meteorite in his museum's courtyard, near where he parks his bicycle. Called *Agpalilik*, Inuit for "the Man," the 20-ton rock is a fragment of an even larger meteorite, the Cape York, found in pieces on northwest Greenland by Western explorers but long used by Inuit people as a source of iron for harpoon tips and tools. Kjær wondered whether the meteorite might be a remnant of an impactor that dug the circular feature under Hiawatha. But he still wasn't confident that it was an impact crater. He needed to see it more clearly with radar, which can penetrate ice and reflect off bedrock.

Kjær's team began to work with Joseph MacGregor, a glaciologist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, who dug up archival radar data. MacGregor found that NASA aircraft often flew over the site on their way to survey Arctic sea ice, and the instruments were sometimes turned on, in test mode, on the way out. "That was pretty glorious," MacGregor says.

The radar pictures more clearly showed what looked like the rim of a crater, but they were still too fuzzy in the middle. Many features on Earth's surface, such as volcanic calderas, can masquerade as circles. But only impact craters contain central peaks and peak rings, which form at the center of a newborn crater when—like the splash of a stone in a pond—molten rock rebounds just after a strike. To look for those features, the researchers needed a dedicated radar mission.

Coincidentally, the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany, had just purchased a next-generation ice-penetrating radar to mount across the wings and body of their Basler aircraft, a twin-propeller retrofitted DC-3 that's a workhorse of Arctic science. But they also needed financing and a base close to Hiawatha.

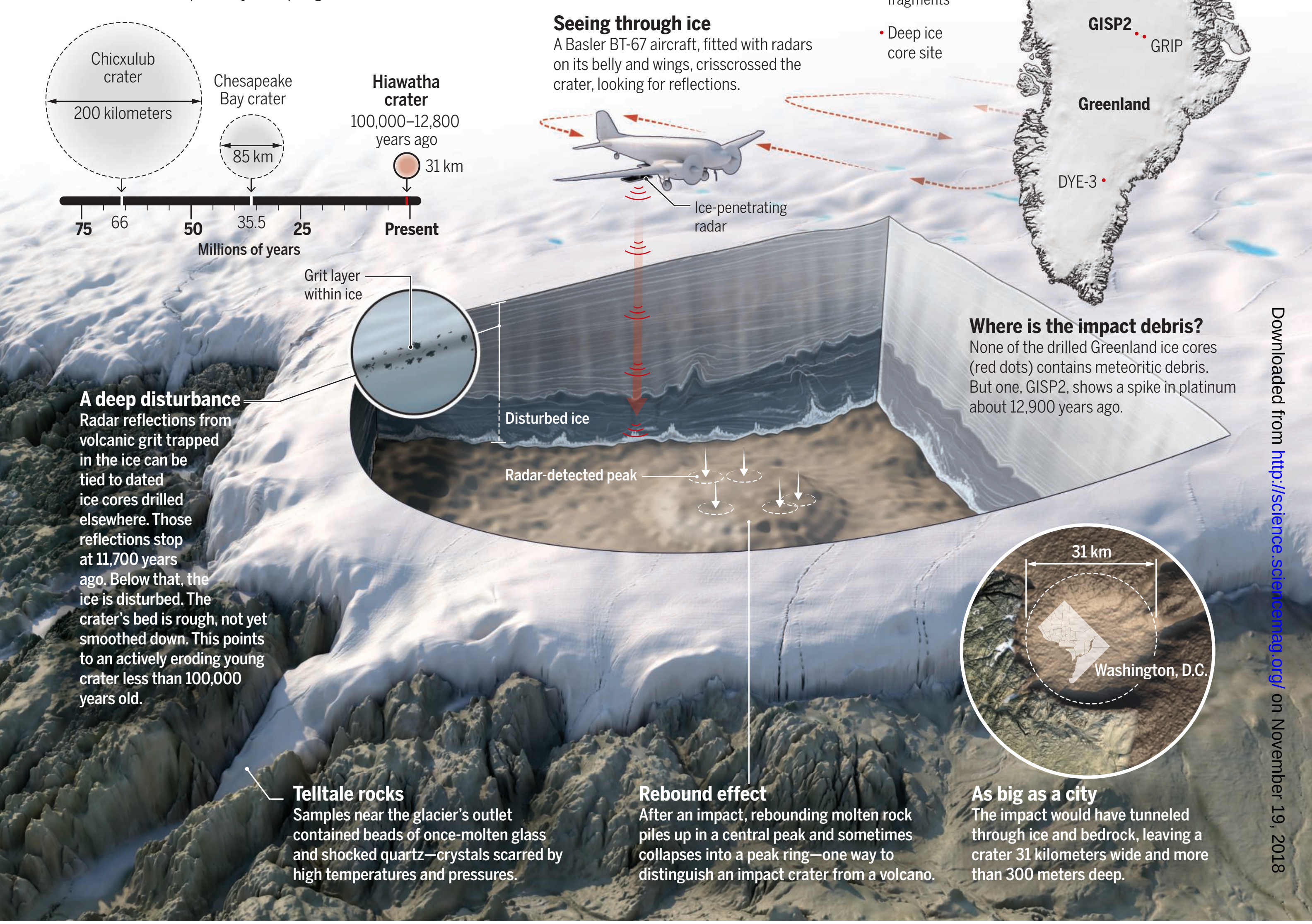
Kjær took care of the money. Traditional funding agencies would be too slow, or prone to leaking their idea, he thought. So he petitioned Copenhagen's Carlsberg Foundation, which uses profits from its global beer sales to finance science. MacGregor, for his part, enlisted NASA colleagues to persuade the U.S. military to let them work out of Thule Air Base, a Cold War outpost on northern Greenland, where German members of the team had been trying to get permission to work for 20 years. "I had retired, very serious German scientists sending me happy-face emojis," MacGregor says.

Three flights, in May 2016, added 1600 kilometers of fresh data from dozens of transits across the ice—and evidence that Kjær, MacGregor, and their team were onto something. The radar revealed five prominent bumps in the crater's center, indicating a central peak rising some 50 meters high. And in a sign of a recent impact, the crater bottom is exceptionally jagged. If the asteroid had struck earlier than 100,000 years ago, when the area was ice free, erosion from melting ice farther inland would have scoured the crater smooth, MacGregor says. The radar signals also showed that the deep layers of ice were jumbled up—another sign of a recent impact. The oddly disturbed patterns, MacGregor says, suggest "the ice sheet hasn't equilibrated with the presence of this impact crater."

But the team wanted direct evidence to overcome the skepticism they knew would greet a claim for a massive young crater, one that seemed to defy the odds of how often large impacts happen. And that's why Kjær found himself, on that bright July day in 2016, frenetically sampling rocks all along the crescent of terrain encircling Hiawatha's face. His most crucial stop was in the middle of the semicircle, near the river, where he collected sediments that appeared to have come from the glacier's interior. It was hectic, he says—"one of those days when you just check your samples, fall on the bed, and don't rise for some time."

The hidden crater

Under a lobe of ice on northwest Greenland, airborne radar and ground sampling have uncovered a giant and remarkably fresh impact crater. Though not as large as the dinosaur-killing Chicxulub impact, Hiawatha crater may have formed as recently as the end of the last ice age, as humans were spreading across North America. Meltwater from the impact could have triggered a thousand-year chill in the Northern Hemisphere by disrupting currents in the Atlantic Ocean.



In that outwash, Kjær's team closed its case. Sifting through the sand, Adam Garde, a geologist at the Geological Survey of Denmark and Greenland in Copenhagen, found glass grains forged at temperatures higher than a volcanic eruption can generate. More important, he discovered shocked crystals of quartz. The crystals contained a distinctive banded pattern that can be formed only in the intense pressures of extraterrestrial impacts or nuclear weapons. The quartz makes the case, Melosh says. "It looks pretty good. All the evidence is pretty compelling."

Now, the team needs to figure out exactly when the collision occurred and how it affected the planet.

THE YOUNGER DRYAS, named after a small white and yellow arctic flower that flourished during the cold snap, has long fascinated scientists. Until human-driven global warming set in, that period reigned as one of the sharpest recent swings in temperature on Earth. As the last ice age waned, about 12,800 years ago, temperatures in parts of the Northern Hemisphere plunged by as much as 8°C, all the way back to ice age readings. They stayed that way for more than 1000 years, turning advancing forest back into tundra.

The trigger could have been a disruption in the conveyor belt of ocean currents, including the Gulf Stream that carries heat northward from the tropics. In a 1989 paper in *Nature*, Kennett, along with Wallace Broecker, a climate scientist at Columbia University's Lamont-Doherty Earth Observatory, and others, laid out how meltwater from retreating ice sheets could have shut down the conveyor. As warm water from the tropics travels north at the surface, it cools while evaporation makes it saltier. Both factors boost the water's density until it sinks into the abyss, helping to drive the conveyor. Adding a pulse of less-dense freshwater could hit the brakes. Paleoclimate researchers have largely endorsed the idea, although evidence for such a flood has been lacking until recently.

Then, in 2007, Kennett suggested a new trigger. He teamed up with scientists led by

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Richard Firestone, a physicist at Lawrence Berkeley National Laboratory in California, who proposed a comet strike at the key moment. Exploding over the ice sheet covering North America, the comet or comets would have tossed light-blocking dust into the sky, cooling the region. Farther south, fiery projectiles would have set forests alight, producing soot that deepened the gloom and the cooling. The impact also could have destabilized ice and unleashed meltwater that would have disrupted the Atlantic circulation.

The climate chaos, the team suggested, could explain why the Clovis settlements emptied and the megafauna vanished soon afterward. But the evidence was scanty. Firestone and his colleagues flagged thin sediment layers at dozens of archaeological sites in North America. Those sediments seemed to contain geochemical traces of an extraterrestrial impact, such as a peak in iridium, the exotic element that helped cement the case for a Chicxulub impact. The layers also yielded tiny beads of glass and iron—possible meteoritic debris—and heavy loads of soot and charcoal, indicating fires.

The team met immediate criticism. The decline of mammoths, giant sloths, and other species had started well before the Younger Dryas. In addition, no sign existed of a human die-off in North America, archaeologists said. The nomadic Clovis people wouldn't have stayed long in any site. The distinctive spear points that marked their presence probably vanished not because the people died out, but rather because those weapons were no longer useful once the mammoths waned, says Vance Holliday, an archaeologist at The University of Arizona in Tucson. The impact hypothesis was trying to solve problems that didn't need solving.

The geochemical evidence also began to erode. Outside scientists could not detect the iridium spike in the group's samples. The beads were real, but they were abundant across many geological times, and soot and charcoal did not seem to spike at the time of the Younger Dryas. "They listed all these things that aren't quite sufficient," says Stein Jacobsen, a geochemist at Harvard University who studies craters.

Yet the impact hypothesis never quite died. Its proponents continued to study the putative debris layer at other sites in Europe and the Middle East. They also reported finding microscopic diamonds at different sites that, they say, could have been formed only by an impact. (Outside researchers question the claims of diamonds.)

Now, with the discovery of Hiawatha crater, "I think we have the smoking gun," says Wendy Wolbach, a geochemist at DePaul University in Chicago, Illinois, who has done work on fires during the era.

The impact would have melted 1500 gigatons of ice, the team estimates—about as much ice as Antarctica has lost because of global warming in the past decade. The local greenhouse effect from the released steam and the residual heat in the crater rock would have added more melt. Much of that freshwater could have ended up in the nearby Labrador Sea, a primary site pumping the Atlantic Ocean's overturning circulation. "That potentially could perturb the circulation," says Sophia Hines, a marine paleoclimatologist at Lamont-Doherty.

Leery of the earlier controversy, Kjær won't endorse that scenario. "I'm not putting myself in front of that bandwagon," he says. But in drafts of the paper, he admits, the team explicitly called out a possible connection between the Hiawatha impact and the Younger Dryas.

THE EVIDENCE STARTS with the ice. In the radar images, grit from distant volcanic eruptions makes some of the boundaries between seasonal layers stand out as bright reflections. Those bright layers can be matched to the same layers of grit in cataloged, dated ice cores from other parts of Greenland. Using that technique, Kjær's team found that most ice in Hiawatha is perfectly layered through the past 11,700 years. But in the older, disturbed ice below, the bright reflections disappear. Tracing the deep layers, the team matched the jumble with debris-rich surface ice on Hiawatha's edge that was previously dated to 12,800 years ago. "It was pretty self-consistent that the ice flow was heavily disturbed at or prior to the Younger Dryas," MacGregor says.

Other lines of evidence also suggest Hiawatha could be the Younger Dryas impact. In 2013, Jacobsen examined an ice core from the center of Greenland, 1000 kilometers away. He was expecting to put the Younger Dryas impact theory to rest by showing that, 12,800 years ago, levels of metals that asteroid impacts tend to spread did not spike. Instead, he found a peak in platinum, similar to ones measured in samples from the crater site. "That suggests a connection to the Younger Dryas right there," Jacobsen says.

For Broecker, the coincidences add up. He had first been intrigued by the Firestone paper, but quickly joined the ranks of naysayers. Advocates of the Younger Dryas impact pinned too much on it, he says: the fires, the extinction of the megafauna, the abandonment of the Clovis sites. "They put a bad shine on it." But the platinum peak Jacobsen found, followed by the discovery of Hiawatha, has made him believe again. "It's got to be the same thing," he says.

Yet no one can be sure of the timing. The disturbed layers could reflect nothing more than normal stresses deep in the ice sheet. "We know all too well that older ice can be lost by shearing or melting at the base," says Jeff Severinghaus, a paleoclimatologist at the Scripps Institution of Ocean-

NASA and German aircraft used radar to see the contours of an impact crater beneath the ice of Hiawatha Glacier.

PHOTO: JOHN SONNTAG/NASA

In 2016, Kurt Kjær looked for evidence of an impact in sand washed out from underneath Hiawatha Glacier. He would find glassy beads and shocked crystals of quartz.

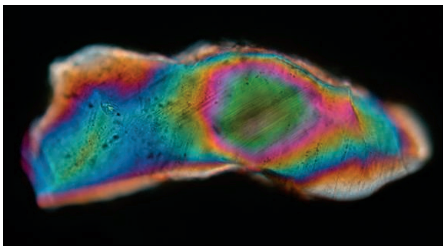
ography in San Diego, California. Richard Alley, a glaciologist at Pennsylvania State University in University Park, believes the impact is much older than 100,000 years and that a subglacial lake can explain the odd textures near the base of the ice. "The ice flow over growing and shrinking lakes interacting with rough topography might have produced fairly complex structures," Alley says.

A recent impact should also have left its mark in the half-dozen deep ice cores drilled at other sites on Greenland, which document the 100,000 years of the current ice sheet's history. Yet none exhibits the thin layer of rubble that a Hiawatha-size strike should have kicked up. "You really ought to see something," Severinghaus says.

Brandon Johnson, a planetary scientist at Brown University, isn't so sure. After seeing a draft of the study, Johnson, who models impacts on icy moons such as Europa and Enceladus, used his code to recreate an asteroid impact on a thick ice sheet. An impact digs a crater with a central peak like the one seen at Hiawatha, he found, but the ice suppresses the spread of rocky debris. "Initial results are that it goes a lot less far," Johnson says.

EVEN IF THE ASTEROID struck at the right moment, it might not have unleashed all the disasters envisioned by proponents of the Younger Dryas impact. "It's too small and too far away to kill off the Pleistocene mammals in the continental United States," Melosh says. And how a strike could spark flames in such a cold, barren region is hard to see. "I can't imagine how something like this impact in this location could have caused massive fires in North America," Marlon says.

It might not even have triggered the Younger Dryas. Ocean sediment cores show no trace of a surge of freshwater into the Labrador Sea from Greenland, says Lloyd Keigwin, a paleoclimatologist at the Woods Hole Oceanographic Institution in Massachusetts. The best recent evidence, he adds, suggests a flood into the Arctic Ocean through western Canada instead.



Banded patterns in the mineral quartz are diagnostic of shock waves from an extraterrestrial impact.

An external trigger may be unnecessary in any case, Alley says. During the last ice age, the North Atlantic saw 25 other cooling spells, probably triggered by disruptions to the Atlantic's overturning circulation. None of those spells, known as Dansgaard-Oeschger (D-O) events, was as severe as the Younger Dryas, but their frequency suggests an internal cycle played a role in the Younger Dryas, too. Even Broecker agrees that the impact was not the ultimate cause of the cooling. If D-O events represent abrupt transitions between two regular states of the ocean, he says, "you could say the ocean was approaching instability and somehow this event knocked it over."

Still, Hiawatha's full story will come down to its age. Even an exposed impact crater can be a challenge for dating, which requires capturing the moment when the impact altered existing rocks—not the original age of the impactor or its target. Kjær's team has been trying. They fired lasers at the glassy spherules to release argon for dating, but the samples were too contaminated. The researchers are inspecting a blue crystal of the mineral apatite for lines left by the decay of uranium, but it's a long shot. The team also found traces of carbon in other samples, which might someday yield a date, Kjær says. But the ultimate answer may require drilling through the ice to the crater floor, to rock that melted in the impact, resetting its radioactive clock. With large enough samples, researchers should be able to pin down Hiawatha's age.

Given the remote location, a drilling expedition to the hole at the top of the world would be costly. But an understanding of recent climate history—and what a giant impact can do to the planet—is at stake. "Somebody's got to go drill in there," Keigwin says. "That's all there is to it." ■

IMAGES: (TOP TO BOTTOM) SVEND FUNDER; ADAM GARDE, GEUS

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Ice age impact

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